Note: A Separation Principle for a Class of Assemble-to-Order Systems with Expediting

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In an assemble-to-order system, a wide variety of products are rapidly assembled from component inventories in response to customer orders. We assume that orders must be filled within a product-specific target lead time. In the event that some of the components required to fill an order are out of stock, these components must be expedited. The objective is to minimize the expected infinite-horizon discounted cost of primary component production and expediting. Our formulation captures financial holding costs but implicitly assumes that physical holding costs are negligible. The controls are (1) sequencing orders for assembly, (2) primary component production, and (3) component expediting. We prove that the multidimensional assemble-to-order control problem separates into single-item inventory control problems. In particular, under an optimal policy for assembly sequencing, the optimal production and expediting policy for each component is independent of all other components. Hence, the literature on single-item inventory management with expediting or lost sales is directly relevant to the control of assemble-to-order systems.

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1. Introduction

An assemble-to-order manufacturer offers a family of products that can be assembled rapidly, in response to a customer’s order, from an inventory of a relatively small number of modular components. When one of these components is in shortage, the manufacturer must expedite the component or delay fulfillment of some customers’ orders. Some manufacturers fill customer orders FIFO (Agrawal and Cohen 2001), but Dell uses real-time information to jointly optimize component expediting and the sequencing of orders for assembly (Perman 2001). Dynamic control of an assemble-to-order system is challenging because the state space (outstanding orders and their due dates, and the inventory and production status for each component) is very large.

The structure of an optimal policy for an assemble-to-order system can be very complex. In general, the decision of when and how much to produce of one component cannot be made without knowledge of the inventory levels of other components. Benjaafar and ElHafsi (2006) show that component inventories in an assembly system with one product are complementary: The optimal inventory level for one component increases with the inventory of every other component. Kushner (1999) and Plambeck and Ward (2005, 2006) solve Brownian control problems that approximate the integrated optimal production of components; with multiple products, inventories of some components may be substitutes rather than complements.

Both for purposes of analytic tractability and policy implementation, assuming the inventory of any given component is managed independently of all other components makes sense. Many authors have assumed independent base-stock control of each component, and then characterized system performance and the best base-stock levels. A common formulation is to choose the base-stock levels to minimize inventory holding costs, subject to a lower bound on the fill rate (fraction of customer orders assembled within the target lead time). We refer the reader to Song and Zipkin (2003), who provide an excellent survey of the extensive literature on control of assemble-to-order systems. More recently, Lu and Song (2005) have provided expressions for the “surrogate backorder penalty” to separate the problem of computing the best base-stock levels for the assemble-to-order system into simple, single-item inventory management problems. The best base-stock level in a single-item system with the surrogate backorder penalty is approximately equal to the best base-stock level for the corresponding component in the assemble-to-order system.
Our purpose is to identify a class of assemble-to-order systems for which the optimal control problem separates: Under an optimal policy, one manages production and inventory of each component independently of the status of other components. Our problem formulation allows both component production and the sequencing of orders for assembly to be dynamic control decisions. The control problem is to minimize the expected infinite-horizon discounted cost of component production subject to assembling all orders for a given product within the product-specific target lead time. This discounted formulation accounts for the financial costs of holding component inventory (including obsolescence), but not physical holding costs. The key assumptions for separation to occur are:

**Assumption 1.** Physical holding costs are negligible.

**Assumption 2.** Early assembly would not induce early payment from a customer.

**Assumption 3.** Components are expedited, if necessary, to fill every customer order within the product-specific target lead time.

An important consequence of the separation principle is that existing results for single-item inventory management with lost sales or expediting can be leveraged to characterize optimal policies for the aforementioned class of assemble-to-order systems.

The purpose of Assumptions 1, 2, and 3 is to guarantee that an optimal policy assembles orders at their due dates. Assumption 3 guarantees that such a policy is feasible. Assumptions 1 and 2 imply that the manufacturer will wait as long as possible to assemble customer orders to maintain flexibility with how to use component inventory. Without either Assumption 1 or 2, an optimal policy might assemble some orders early (before their due dates), at the risk of expediting additional components, to reduce expected costs.

Assumption 1 is a reasonable approximation in the electronics industry, for example, where financial holding costs dominate physical holding costs. Assumption 2 is satisfied if a customer pays when he orders (as for some consumer goods sold on the Internet) or if the customer pays at the promised delivery time (as is typical when the customer is another manufacturer). A substitute for Assumptions 1 and 2 is that the assembler must provide a constant lead time (e.g., the customer is a just-in-time manufacturer that will not accept early delivery), and the physical holding cost for an assembled product is at least as large as the physical holding cost for all its constituent components.

Whereas Assumptions 1 and 2 are reasonable in some important industries, Assumption 3 is restrictive. Some firms do expedite component production when necessary. Descriptions of how Dell, Caterpillar, Hewlett-Packard, Intel, and Oce use expediting can be found in Perman (2001), Rao et al. (2000), Beyer and Ward (2000), and Scheller-Wolf et al. (2004). However, in general, the lead time to expedite components may exceed the target customer order lead time, and so the fill rate will be less than 100%, due to uncertain demand.

In practice, the lead time quoted for each product is a decision variable. Therefore, when the lead time to expedite components is finitely bounded and the cost of violating the product lead time is sufficiently large, an optimal policy will achieve 100% fill rate and satisfy Assumption 3. Graves and Willems (2005) propose a dynamic programming method to design a supply network having 100% fill rate, and apply this in the computer industry.

When Assumption 3 is relaxed, independent component inventory management remains optimal in an approximate sense under other plausible conditions. Two examples follow. First, in a single-product assembly system with capacitated component production and no expediting, Benjaafar and ElHafsi (2006) observe that independent base-stock control of each component is approximately optimal when the backorder penalty is large. Second, in a two-tier assemble-to-order system with capacitated component production, expensive expediting at the component production facility, and batch transportation, Plambeck (2005) proves that independent control of each component is asymptotically optimal as the demand rate grows large.

The remainder of this note is organized as follows. Section 2 formulates the assemble-to-order control problem, and §3 proves that the problem separates into a single-item inventory control problem for each component. Section 4 reviews relevant results for single-item inventory systems with lost sales or expediting.

### 2. Model Formulation

Consider an assemble-to-order system with $M$ components and $J$ products, as shown in Figure 1. Orders for product $j$ arrive according to a stochastic process $D_j(t)$, which denotes the cumulative number of orders for product $j$ up to time $t$ for $j = 1, \ldots, J$ and $t \geq 0$. To assemble a product of type $j$ requires $a_{jm}$ components of type $m$, where $a_{jm}$ is a nonnegative integer. Orders for product $j$ must be assembled within target lead time $l_j$. In other words, an order arriving at time $t$ must be assembled by time $t + l_j$.

We have three controls: sequencing orders for assembly, component production planning, and component expediting. We restrict attention to sequencing policies in which orders for each product $j$ are assembled FIFO. It is therefore sufficient to specify $A_j(t)$, the cumulative number of product $j$ assembled up to time $t$ for $j = 1, \ldots, J$ and $t \geq 0$. Assembly is instantaneous if the required components are in stock.

The second dynamic control is the production plan $P_m(t)$ for each component $m = 1, \ldots, M$ via the primary supply mode. Actual production may be stochastic, and so may deviate from the plan. The stochastic process $Q_m(t; P_m)$ denotes the cumulative number of components delivered to the assembly facility by time $t$ via the primary supply mode. A per-unit charge of $c_m(t; P_m)$ is assigned to
primary components of type $m$ delivered at time $t$. Disposal or obsolescence are indicated by a decrease in $Q_m(t; P_m)$ as a function of time. If $Q_m(t; P_m) - Q_m(t^-; P_m) < 0$ and $c_m(t; P_m)$ should be interpreted as the per-unit salvage value for the $(Q_m(t^-; P_m) - Q_m(t; P_m))$ items disposed at time $t$.

The third dynamic control is expediting. Additional components may be expedited with a deterministic lead time $\tau_m \geq 0$ to the assembly facility, and $X_m(t)$ denotes the cumulative number of type-$m$ components expedited by time $t$ for $m = 1, \ldots, M$. To ensure that every customer order can be assembled within its target lead time, we assume that

$$\tau_m \leq l_j \quad \text{for all} \quad m = 1, \ldots, M \quad \text{and} \quad j = 1, \ldots, J \quad \text{such that} \quad a_{jm} > 0,$$

and the system manager knows how much primary production can be achieved during the expedite lead time, i.e., the system manager knows $Q_m(t + \tau_m; P_m)$ at time $t$. In our notation, the inventory position at the assembly facility (not including outstanding orders for components) is

$$Q_m(t; P_m) + X_m(t - \tau_m) - \sum_{j=1}^{J} a_{jm} D_j(t).$$

The above quantity comprises the number of components that have been delivered to the assembly facility and not (yet) disposed, less the number of components required to assemble customer orders, up to time $t$. The physical inventory position at the assembly facility is

$$Q_m(t; P_m) + X_m(t - \tau_m) - \sum_{j=1}^{J} a_{jm} A_j(t) \geq 0. \quad (1)$$

Expediting at time $t$ incurs a charge of $x_m(t; X_m)$ per unit expedited. This may, for example, be a constant $x_m$, or include a fixed setup or transportation cost. Alternatively, $x_m(t; X_m)$ may increase with the order quantity $X_m(t) - X_m(t^-)$.

Three examples follow to illustrate the high level of generality in the production plan model. First, $P_m(t)$ could be the number of orders for component $m$ issued up to time $t$. Suppose for the moment that component production is uncapacitated, transportation lead times are i.i.d. random variables $d_j$, and there is a fixed cost $F$ and variable cost $v$ for each order. Let $T_i$ denote the time at which the $i$th order is placed (the $i$th jump in the process $P_m(t)$), so that $(P_m(T_i) - P_m(T_i^-))$ is the $i$th order quantity. Then, primary production is given by

$$Q_m(t; P_m) = \sum_{i=1}^{P_m(t)} 1\{T_i + d_i \leq t\}(P_m(T_i) - P_m(T_i^-)), \quad (2)$$

where $1\{\}$ is the indicator function, and the per-unit cost is

$$c_m(T_i + d_i; P_m) = v + F/(P_m(T_i) - P_m(T_i^-)).$$

Alternatively, if the lead time for primary production is a stochastic-sequential process $L_m(t)$, then

$$Q_m(t + L_m(t); P_m) = P_m(t).$$

As a third illustrative example, $P_m(t)$ could be the amount of time that a production facility dedicates to component $m$ up to time $t$. (Alternatively, $t - P_m(t)$ could be interpreted as cumulative idle time.) Then, letting $Z$ be a counting process, primary production is given by

$$Q_m(t; P_m) = Z(P_m(t)). \quad (3)$$

Here, $P_m(t)$ must be nondecreasing and satisfy $P_m(t) \leq t$.

In summary, $P$ is what the system manager decides to do, and $Q$ is the result of that decision. For all three examples, the simple assumption $\tau_m = 0$ for all $m = 1, \ldots, M$ ensures that the system manager knows how much primary production can be achieved during the expedite lead time.

We impose the following technical assumptions. All underlying random variables are defined on the same probability space $(\Omega, \mathcal{F}, \mathbb{P})$. The primitives $(D_j(t))_{j=1}^{J}$ and $(Q_m(t + \tau_m))_{m=1}^{M}$ are adapted to the filtration $\mathcal{F}_t$, and the control processes $(A_j(t))_{j=1}^{J}$ and $(P_m(t), X_m(t))_{m=0}^{M}$ must be nonanticipating with respect to the filtration $\mathcal{F}_t$. In particular, this means that $P_m(t)$ and $Q_m(t + \tau_m; P_m)$ are $\mathcal{F}_t$-measurable. (The lead time for a change in the production plan to influence basic component production is longer than the lead time for expediting component production.) Furthermore, $(D, A, X, Q)$ are nondecreasing, and $(D, A, X, Q)$ are nonnegative, integer valued, and RCLL (right continuous with left limits). For each $t$, the ongoing demand process $D_j(s)_{s \leq t}$ is independent of $(A(s), P(s), Q(s), X(s))_{0 \leq s \leq t}$. Conditional on the planned production $P_m$ and expediting $X_m$, the primary component production and cost processes $(Q_m(\cdot; P_m), c_m(\cdot; P_m), x_m(\cdot; X_m))$ are independent of $((Q(\cdot; P), c_j(\cdot; P_j), P_j, x_i(\cdot; X_i)), X_i)_{i \neq m}$. The qualitative
interpretation of this assumption is that the actual production of each component $m$ is independent of production of all other components.

The control problem is to minimize the expected infinite horizon discounted cost of primary component production and expediting, subject to assembling orders for product $j$ within the target lead time $l_j$, for a given discount rate $\delta > 0$:

$$\min_{A, P, X} E \left[ \sum_{m=1}^{M} \left( \int_0^\infty e^{-\delta t} c_m(t; P_m) \, dQ_m(t; P_m) + \int_0^\infty e^{-\delta t} x_m(t; X_m) \, dX_m(t) \right) \right]$$

subject to

$$A_j(t) \geq D_j(t - l_j) \quad \text{for } t \geq 0 \text{ and } j = 1, \ldots, J,$$  

$$\sum_{j=1}^{J} a_{jm} A_j(t) \leq Q_m(t; P_m) + X_m(t - \tau_m)$$

for $t \geq 0$ and $m = 1, \ldots, M$,  

$$A, P, X \text{ are nonanticipating},$$

$$A, X \text{ are nonnegative, integer valued, nondecreasing, and RCLL.}$$

The integrals should be interpreted as Riemann-Stieltjes integrals in the usual sense. Constraint (5) ensures 100% fill rate within the target lead time. Constraint (6) dictates that products cannot be assembled without the required components, so that the physical inventory level at the assembly facility in (1) remains nonnegative. Supply constraints could be incorporated by setting $c_m(t, P_m) = \infty$ for any primary production plan $P_m$ that is infeasible. This problem formulation captures financial inventory holding costs incurred when components are produced before they are required for assembly, but does not capture physical inventory holding costs. Because $c_m$ is typically smaller than $x_m$, the objective function evidences the trade-off between ordering cheap components with longer lead times and purchasing expensive components with a short lead time.

3. Separation Principle

We will now show how to separate the assemble-to-order control problem (4)–(8) into $M$ single-item inventory control problems, one for each component. The first step is to characterize an optimal policy for assembly and expediting. In particular, an optimal policy for assembly sequencing is to assemble each order when it is due.

**Proposition 1.** Given the primary production plan $P$, an optimal policy for assembly sequencing is

$$A^*_j(t) = D_j(t - l_j) \quad \text{for } t \geq 0 \text{ and } j = 1, \ldots, J,$$

and the optimal policy for expediting must satisfy

$$X^*_m(t) \geq \sup_{0 \leq \tau_m \leq l_j} \left[ \sum_{j=1}^{J} a_{jm} D_j(s + \tau_m - l_j) - Q_m(s + \tau_m; P_m) \right]^+$$

for $t \geq 0$ and $m = 1, \ldots, M$.  

If the per-unit cost of expediting $x_m(t; X_m)$ is nondecreasing in the number expedited $\{X_m(s)\}_{0 \leq s \leq t}$, and nonincreasing in time, then the optimal policy for expediting is

$$X^*_m(t) = \sup_{0 \leq \tau_m \leq l_j} \left[ \sum_{j=1}^{J} a_{jm} D_j(s + \tau_m - l_j) - Q_m(s + \tau_m; P_m) \right]^+$$

for $t \geq 0$ and $m = 1, \ldots, M$.  

**Proof.** For a given $t$ and for any $m = 1, \ldots, M$, the minimum value of $X_m(t)$ that satisfies (6) is

$$X_m(t) = \sum_{j=1}^{J} a_{jm} A_j(t + \tau_m) - Q_m(t + \tau_m; P_m).$$

Because the expediting process $X_m(t)$ must be nonnegative and nondecreasing, the minimal amount of expediting required to satisfy (6) is

$$X_m(t) = \sup_{0 \leq \tau_m \leq l_j} \left[ \sum_{j=1}^{J} a_{jm} A_j(s + \tau_m) - Q_m(s + \tau_m; P_m) \right]^+.$$  

Therefore, $X_m(t)$ is nondecreasing with $A_j(s)_{0 \leq s \leq t}$. Assembling an order before its due date tightens constraint (6), increasing expediting if the necessary components are not already in stock. Therefore, an optimal assembly policy is to assemble orders exactly when they are due: $A^*_j(t) = D_j(t - l_j)$ is the minimal assembly needed to satisfy constraint (5). Substituting $A^*_j(t)$ into (12) gives the right-hand side of (10). The inequality may be strict (components are expedited earlier than necessary) because the per-unit cost of expediting $x_m(t; X_m)$ may decrease in the order quantity or increase in time.

Finally, suppose that the per-unit cost of expediting $x_m(t; X_m)$ is nondecreasing in the number expedited $\{X_m(s)\}_{0 \leq s \leq t}$, and nonincreasing in time $t$. Because

$$X^*_m(t) = \sup_{0 \leq \tau_m \leq l_j} \left[ \sum_{j=1}^{J} a_{jm} D_j(s + \tau_m - l_j) - Q_m(s + \tau_m; P_m) \right]^+$$

is the smallest feasible value of $X_m(t)$ for all $t \geq 0$ and $m = 1, \ldots, M$, it minimizes the infinite-horizon discounted cost of expediting on every sample path $\omega \in \Omega$. That $D_j(t)$, $P_m(t)$, and $Q_m(t + \tau_m; P_m)$ are $\mathcal{F}_t$-measurable, and $\tau_m \leq l_j$ for all $m = 1, \ldots, M$ and $j = 1, \ldots, J$ such that $a_{jm} > 0$, ensures that $X^*_m(t) = \sup_{0 \leq \tau_m \leq l_j} \left[ \sum_{j=1}^{J} a_{jm} D_j(s + \tau_m - l_j) - Q_m(s + \tau_m; P_m) \right]^+$ is nonanticipating. \(\square\)

It follows immediately from Proposition 1 that optimal production and expediting for component $m$ does not depend on the production and expediting of other components. Therefore, problem (4)–(8) separates into $M$ single-item inventory control problems, one for each component $m$:

$$\min_{P, X_m} E \left[ \int_0^\infty e^{-\delta t} c_m(t; P_m) \, dQ_m(t; P_m) \right.$$  

$$+ \int_0^\infty e^{-\delta t} x_m(t; X_m) \, dX_m(t) \]$$
subject to
\[
X_m(t) \geq \sup_{0 \leq s \leq t} \left[ \sum_{j=1}^{J} d_{jm} D_j (s + \tau_m - l_j) - Q_m (s + \tau_m; P_m) \right]^+ 
\]
for \( t \geq 0 \), \( (14) \)

\( P_m \) and \( X_m \) are nonanticipating.
\( X_m \) is nonnegative, integer valued, nondecreasing, and RCLL. \( (15) \)

This separation greatly simplifies the optimal control problem for the assemble-to-order system.

### 4. Single-Item Inventory Management with Expediting

In §4.1, we review the literature on single-item inventory management with lost sales, which analyzes problem \( (13)-(15) \) with zero expedite lead time: \( \tau_m = 0; \) zero order lead time: \( l_j = 0 \) for \( j = 1, \ldots, J \); and constant expedite cost per unit: \( x_m(t; X_m) = x > 0 \). In §4.2, we review recent papers on single-item inventory management with a positive lead time for expediting components. These papers offer relevant insights and solution approaches, although their control problems differ somewhat from \( (13)-(15) \). In all papers reviewed in this section, orders are assumed to arrive according to a Poisson process.

#### 4.1. Lost Sales (Zero Expedite Lead Time)

Suppose that primary component production is a Poisson process, a special case of the third illustrative example (3). Furthermore, the cost per unit of primary production is constant. Then, the optimal policy idles primary component production when the inventory position reaches a base-stock level (Veatch and Wein 1996). Bertsekas (2000) extends this result to a setting in which the primary production rate \( \mu_m \) can be changed at times when a component is completed or an order arrives, and the per-unit cost is an increasing and convex function \( c_m(\mu_m) \): The optimal production rate \( \mu_m^* \) decreases with the inventory position.

Alternatively, consider a special case of the first illustrative example (2) with constant component lead time: \( d_i = d \). For this case, Hill (1999) proved that a base-stock policy is suboptimal. Insofar as outstanding orders for components will be delivered soon, one expects fewer lost sales during the next \( d \) units of time, and should therefore maintain a larger component inventory position. Johansen (2001) assumes that orders for primary production must be issued periodically, and characterizes the complex optimal policy. Then, he proposes a simple, modified base-stock policy that performs well in numerical examples. For systems in which at most one order may be outstanding, Johansen and Thorstenson (1993, 1996) both incorporate a fixed cost of placing an order for components, and prove that a continuous review \( (r, Q) \) policy is optimal; Johansen and Hill (2000) provide heuristics for a periodic-review system with a general continuous demand distribution and fixed cost of placing an order.

In case the component lead times \( d_i \) in the first illustrative example (2) are random, analytic characterization of the structure of an optimal policy seems impossible. Nahmias (1979) and Donselaar and Rutten (1996) propose heuristic policies. With base-stock control of primary production and the assumption that orders for primary production do not cross, the expected discounted holding and lost-sales cost is a convex function of the base-stock level (Janakiraman and Roundy 2004). This justifies the use of a simple search procedure to derive the best base-stock level.

All of the results surveyed above are relevant when primary production and expedited production are drawn from separate sources of supply or separate modes of transportation. With a common source, expediting depletes the potential for primary production in the immediate future. Lawson and Porteus (2000) consider dynamic management of lead times in a periodic-review, serial multiechelon system. In each period, the manager at each stage decides how much inventory to hold, how much to transport to the next stage (with a one-period lead time), and how much to expedite instantaneously to the next stage. Expediting to the next stage incurs a higher cost per unit. They prove that a simple “top-down base-stock policy” minimizes expected holding, transportation, and backorder costs.

#### 4.2. Positive Expedite Lead Time

For an excellent survey of the early literature on single-item inventory systems with a positive lead time for expediting, we refer the reader to Lawson and Porteus (2000). In the past few years, several researchers have made further progress. Feng et al. (2005) characterize optimal policies for systems with multiple modes of transportation, characterized by deterministic, consecutive lead times. With two modes of transportation with general deterministic lead times, the optimal policy is extremely complex (Whitmore and Saunders 1997), but Scheller-Wolf et al. (2004) propose an attractively simple yet effective policy. Scheller-Wolf and Veeraraghavan (2004) and Yi and Scheller-Wolf (2003) incorporate constraints on the primary production per period, and a fixed cost of expediting. Sethi et al. (2003) incorporate fixed ordering costs and forecast updates. Vlachos and Tagaras (2001) assume limited capacity for expediting, and choose a fixed time for expediting within each review period. Tomlin (2006) models disruption at the primary supplier, and expediting from an alternative supplier with limited capacity. Groenevelt and Rudi (2002) model a periodic production decision, followed by the choice of expedited or regular transportation. They obtain an exact solution by assuming that the expedite lead time is sufficiently short so that production orders do not cross.
Bertsekas (2004, 2005) characterizes optimal capacity and inventory control for an $M/M/1$ system with limited expediting.

**Endnotes**

1. Under the U.S. Fair Credit Billing Act, a merchant may charge a customer before shipment if the order ships within the promised lead time. Credit card issuers allow a preshipment charge for customized items. Many computer manufacturers charge customers when they place an order, although Dell chooses to charge customers at the time of shipment (Fairlie 2004).

2. More specifically, Table 3 in Benjaafar and ElHafsi (2006) shows that the percentage difference between the optimal average cost and that obtained using independent base-stock control (their IBR policy) is decreasing in the backorder penalty. Note that their IBR policy allows the base-stock levels to be optimized jointly, whereas our setting is such that the optimum base-stock level for each component can be found independently.

3. This is a standard assumption in the assemble-to-order literature. Note that one could simply reduce $L_i$ to account for a deterministic assembly time.

4. $L_m(t)$ is a stochastic process satisfying: (1) $t + L_m(t)$ is nondecreasing in $t$ so orders for component $m$ are full-filled FIFO, and (2) $L_m(t)$ is independent of the timing and quantity of orders for component $m$, and of the customer demand process. Stochastic-sequential lead times are defined and motivated by Zipkin (2000), and introduced to the assemble-to-order literature by Zhao and Simchi-Levi (2005).

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**References**


